Chapter

11

# Nitrogen flows and fate in rural landscapes

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## Executive summary

### Nature of the problem

- The transfer of nitrogen by either farm management activities or natural processes (through the atmosphere and the hydrological network) can feed into the N cascade and lead to indirect and unexpected reactive nitrogen emissions.
- This transfer can lead to large N deposition rates and impacts to sensitive ecosystems. It can also promote further $N_2O$ emission in areas where conditions are more favourable for denitrification.
- In rural landscapes, the relevant scale is the scale where N is managed by farm activities and where environmental measures are applied.

### Approaches

- Mitigating nitrogen at landscape scale requires consideration of the interactions between natural and anthropogenic (i.e. farm management) processes.
- Owing to the complex nature and spatial extent of rural landscapes, experimental assessments of reactive N flows at this scale are difficult and often incomplete. It should include measurement of N flows in the different compartments of the environment and comprehensive datasets on the environment (soils, hydrology, land use, etc.) and on farm management.
- Modelling is the preferred tool to investigate the complex relationships between anthropogenic and natural processes at landscape scale although verification by measurements is required. Up to now, no model includes all the components of landscape scale N flows: farm functioning, short range atmospheric transfer, hydrology and ecosystem modelling.

### Key findings/state of knowledge

- The way N is managed, as well as the location of farming activities, can have a strong influence on N flows at landscape scale. Consequently, environmental measures can be more or less effective according to the landscape and farming system, and the interactions between them.
- The magnitude of nitrate transfers and subsequent impacts is linked to the hydrology of the area (e.g. subsurface versus deep hydrological flows).
- Source–sink relationships for atmospheric transfer are linked to land use (e.g. patchiness, hedgerows) and distance between sources and sensitive areas.
- A verified integrated landscape model would be useful for investigating the N flows in rural landscapes, as well as evaluating different N management strategies and environmental measures at the landscape scale.

### Major uncertainties/challenges

- The multiple pathways of N transfer, the interactions between natural and anthropogenic processes and the risk of pollution swapping require complex high resolution modelling. Linkage of the different model components and the verification and uncertainty assessment of the integrated model are major challenges.
- A network of European landscapes, including different climatic conditions, hydrology and farming systems, should be established as case studies to assess the influence of landscape processes on N budgets.
- When designing and implementing new environmental measures, greater attention should be given to the landscape scale in order to take into account processes (such as N deposition to sensitive areas or indirect $N_2O$ emissions) that maximize the efficiency of the measures.

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## Recommendations

- The implementation of environmental measures should consider the variety of landscape types and allow adaptation to local conditions since their effectiveness might vary according to landscape features and farming systems.
- Environmental measures applied to different landscapes and farming systems should be established and evaluated by modelling and verified, if possible, by monitoring once the measures are in place.

## 11.1 Introduction

Rural landscapes, especially in Europe where there is a long history of agriculture and forestry, were mostly shaped by man in the past decades and centuries. For a long time, the concept of landscape was mainly related to its aesthetic quality as a portion of the earth surface captured by human eye. In landscape ecology, landscape is often described using three concepts: patch, corridor, and matrix (Forman and Godron, 1986). Patch is a '*nonlinear surface area differing in appearance from its surroundings*'. The mosaic of patches evolves and changes according to changes in land use (e.g. de(re)forestation, urban/road construction) and succession (e.g. crop rotation, grassland–cropland succession). Corridors are '*narrow strips of land which differ from the matrix on either side*'. Roads and water streams represent landscape corridors, as well as hedgerows, ditches and grassed strips. Roads are 'disturbance corridors', whereas rivers are 'environmental resource corridors'. Matrix is the '*most extensive and most connected landscape element type, and therefore plays the dominant role in the landscape*' functioning. Landscape is thus understood as a spatially heterogeneous mosaic (Forman and Godron, 1981) with interactions between ecological and anthropogenic processes (e.g. farm management, rural development, land conversion). The study of these interactions provides a practical dimension to landscape, because it is at this scale that planning, management, conservation, and land use change occur (Rapport *et al.*, 1998).

This approach of the landscape, which was initially designed for biodiversity issues (Forman, 1997), is relevant to describe the structure of a landscape for other purposes, and can, to some extent, be applied to nitrogen (N) issues (Liu and Taylor, 2002). In European rural landscapes with high inputs of N, cropland/grassland constitutes the matrix in most cases, although in e.g. Northern Europe the matrix might be the forest. The most relevant patches would be hot-spots in emissions or deposition. For instance, the livestock buildings of farmsteads are large point sources of atmospheric ammonia ($NH_3$), forests are patches with potentially large atmospheric deposition rates and wetlands could be patches consisting of sinks for nitrate ($NO_3^-$), but sources for nitrous oxide ($N_2O$). The corridors also have a role in N transfer and transformation, which will make them of specific interest. The rivers and ditches play a key role in $NO_3^-$ transfer and denitrification in riparian zones, as well as water and N retention time. The roads and tracks network influences fertilizer transfer by the farmer and cattle displacements. However, for N issues, the cropland/grassland matrix cannot be considered as a homogeneous medium. It is itself a mosaic of sources and sinks of N according to the crop type, management practices and proximity of reactive N ($N_r$) sources. To this extent, the distinction between matrix and patches is not straightforward. Moreover, N transfers mostly occur through the atmosphere, the hydrological network and farm management, which means that the connectivity between landscape elements for N transfer is different to that for biodiversity issues.

At large spatial scales, either global (Turner *et al.*, 1994) or European scales (Bouma *et al.*, 1998; Meeus, 1993), a variety of regionally differentiated landscapes is observed. This is mainly due to the ecological adaptation to different constraints (such as geology and climate), and due to integration of agriculture production into regional socio-economic context (food industries, transport pathways (e.g. roads, rivers, valleys and urban areas)). The individual patch areas and the spatial density of linear structures may vary over several orders of magnitude depending on the region and landscape in question. In agricultural areas, one of the main driving forces of landscape design processes is the farming system which is often linked to a regional differentiation of agriculture (Westergaard, 2005). As an example, Figure 11.1 shows the difference in land use distribution for two dairy farming systems in Brittany (France) with different levels of intensification.

In this chapter, we first highlight why the landscape scale is relevant for N issues, from the point of view of process analysis, flux estimation and agro-environmental policies. In the two next sections, we analyse how a landscape can be described and what are the processes which are the most relevant at landscape scale compared to plot scale. This leads on to the next section, which examines to what extent modelling is able to simulate landscape scale processes leading to practical application and scenario analysis. In the last section, we discuss the opportunities to integrate the landscape perspective into N assessment and management and conclude with the future challenges at landscape scale.

## 11.2 Why consider the landscape for N issues?

### 11.2.1 The N cascade in rural landscapes

In rural landscapes, $N_r$ mainly comes from fertilizers and livestock production. Plants absorb mineral N and mainly transform it into organic forms. Animals transform organic N from pasture or feed coming from either within or outside the farm into other forms. Hence, most of this N is managed by man. The amount of N that is manipulated, the methods and the timing

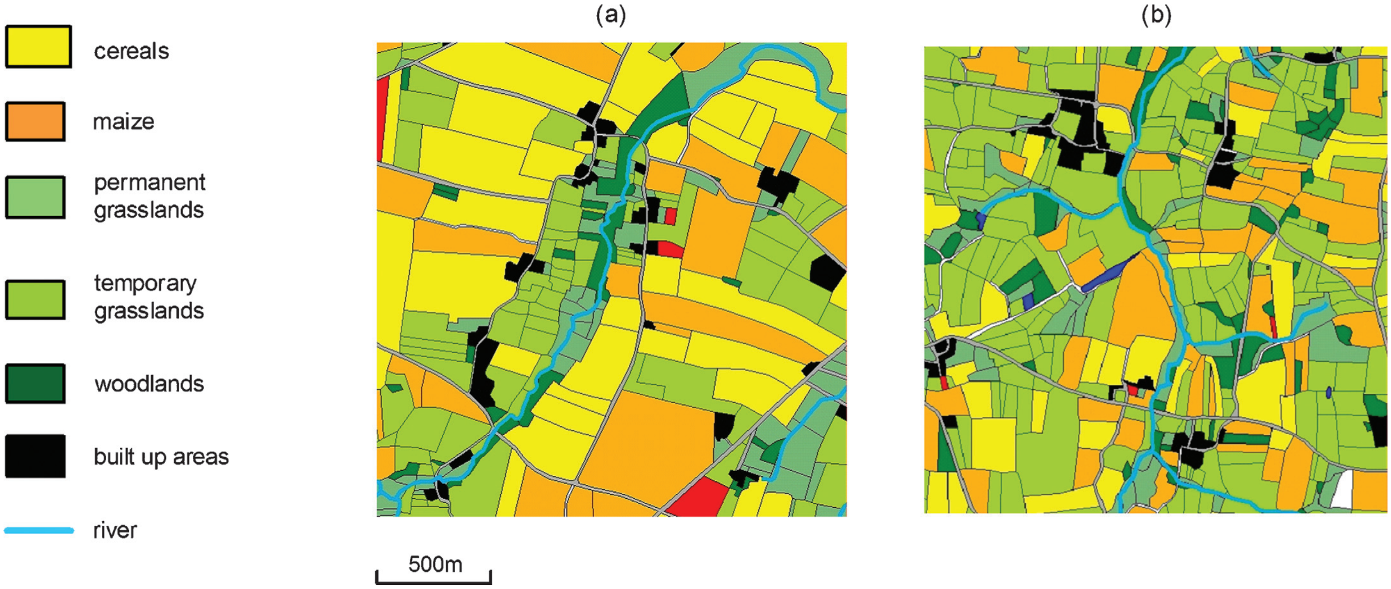


**Figure 11.1** Two landscapes composed of dairy farms in the "Zone-atelier Pleine-Fougéres" in Brittany (western France). In landscape (a), farm areas are large, field patterns are clustered around the farmstead (shown in red) and enable an intensive use of space (large field) with specialized patches of cash crop, forage and pastures. In landscape (b), farms are smaller than in (a); field patterns are fragmented, scattered and dispersed; crops, forage and pastures are very mixed in the landscape giving a heterogeneous crop mosaic.

of production, storage and application depend a lot on farming system and on the production intensity (see Jarvis *et al.*, 2011, Chapter 10, this volume), which are also related to climate and to the links between agriculture and agro-industry.

At field or farmstead scales, processes of N transformation and transfer have been extensively studied, and have given a fair insight into the fate of N at small space and time scales. When going beyond the field or farmstead boundaries (i.e. the landscape, watershed, regional scales), N can be transferred in significant amounts from $N_r$ sources (e.g. farmsteads, field after slurry/fertilizer application, etc.) to the recipient ecosystems by a variety of pathways. For example, atmospheric $NH_3$ emitted from animal housing or a field can be re-deposited to the foliage of nearby ecosystems in amounts that increase the closer the source is horizontally to the recipient ecosystem and vertically to the soil surface (Fowler *et al.*, 1998; Loubet *et al.*, 2006). Similarly, wetlands or crops/grasslands at the bottom of slopes can recapture $NO_3^-$ in the groundwater that originates from N applied further up the slope. In both cases, this can lead to large inputs of N to the receptor ecosystem that may have potential impacts on the ecosystem (Pitcairn *et al.*, 2003) and the biogeochemical cycles, possibly leading to enhanced $N_2O$ and NO emission (Beaujouan *et al.*, 2001; Skiba *et al.*, 2004) and further feeding the N cascade (Galloway *et al.*, 2003) (Figure 11.2). These $N_2O$ emissions resulting from N transfer in receptor ecosystem are usually called indirect emissions and may represent a significant fraction of total $N_2O$ emissions, although how much remains uncertain (Mosier *et al.*, 1998). The importance of uncultivated or marginal areas that are outside or peripheral to the agricultural systems for flows and budgets of energy and matter, including N, emphasizes the need to adopt a landscape perspective.

### 11.2.2 Consequences of heterogeneity on N flows and budgets

When going from the plot scale to the landscape scale, one major new feature that appears is the heterogeneity in land use, in natural features and in farming activities (location of fields/grasslands/forests/ditches, hedgerows, livestock holdings, N application). A range of processes linked to the spatial heterogeneity, either natural or anthropogenic (mainly farm scale), has to be considered, such as non-random application of N at farm scale and the interaction between the farmstead and landscape features (e.g. soil, topography), $NH_3$ transfer and deposition to vegetation, especially forest and hedgerows, $N_2O$ emissions from wetlands and streams, preferential pathways for N through the ditches and tree belts networks. As a whole, the fluxes of deposition (atmosphere) or recapture (groundwater) are most important when N flows from one system to another with different characteristics (see e.g., Beaujouan *et al.*, 2001; Loubet *et al.*, 2009). For example, the deposition of $NH_3$ is especially large at forest edges because the abrupt change in canopy type/height increases the turbulent exchange and the surface area of vegetation in contact with the plume from a nearby source (Fowler *et al.*, 1998; Weathers *et al.*, 2001). This leads to hot-spots in deposition (Dragosits *et al.*, 2002). For example, Loubet *et al.* (2009) estimated that a forest belt can capture more than 15% of the emission from an animal house. For hydrological transfer, Beaujouan *et al.* (2001) estimated – by modelling the water and N flow through the hydrological network, including possible N removal by soil/plants in wetlands and denitrification – that most of $N_2O$ emission is expected to occur in wetlands, i.e. in places where N has not been directly applied but has been transported by hydrological transfer (Oehler *et al.*, 2009; Figure 11.3). Beaujouan *et al.*

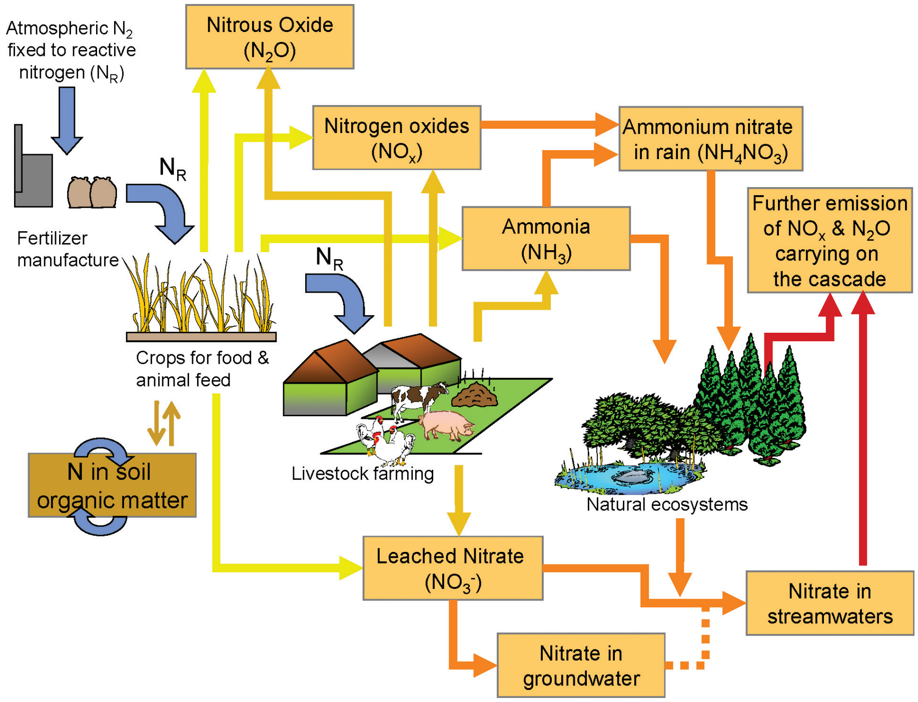


**Figure 11.2** The Nitrogen Cascade in rural landscapes (adapted from Sutton *et al.*, 2011, Chapter 1, this volume).

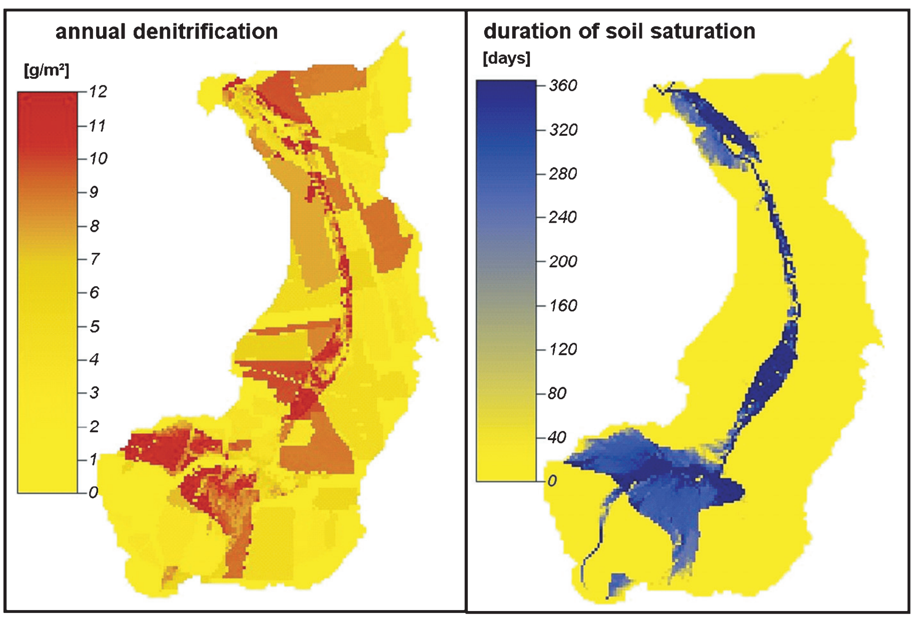


**Figure 11.3** Modelling of the spatio-temporal extension of soil saturation due to the rise of groundwater table (left) and subsequent denitrification (right) using the TNT2 model in a rural catchment (Britanny, France). After Oehler *et al.*, 2009 (modified) and unpublished data.

(2001) also suggested that the recapture of aqueous $NO_3^-$ was greatest when landscape fragmentation was largest and sources and sinks more intimately mixed.

## 11.2.3 Landscape as a scale to mitigate adverse effects of N

Processes of either recapture or transformation of N can be used for mitigating fluxes at larger scale than the scale at which the $N_r$ is applied or produced. An example can be given for the case of $NH_3$. Agricultural sources of $NH_3$ are, by their nature, quite localized, e.g. a fertilized field or an animal house. This means that the exposure of a receptor and the related deposition is largely determined by the spatial relationships between the receptor and the nearby sources. Hence, by deliberately locating 'sink' vegetation downwind of a source, the local recapture of atmospheric $NH_3$ and the enhancement of turbulent mixing in the low atmosphere can be used to mitigate the impacts of atmospheric $NH_3$ further downwind by reducing the concentration within the plume near the surface (Theobald *et al.*, 2001; Dragosits *et al.*, 2006; Loubet *et al.*, 2009). Possible strategies include planting of tree belts (to enhance local deposition and dispersion) in order to reduce the $NH_3$ deposition to sensitive receptors further downwind (Sutton *et al.*, 2004).

Similarly, restoration, management or even construction of wetlands (riparian strips, slow flowing meanders, ponds, etc.) along the course of small rural streams has often been proposed as an efficient measure to mitigate surface water contamination by $NO_3^-$ leaching from agricultural land (Haycock *et al.*, 1997; Woltemade, 2000; Tanner *et al.*, 2003). Indeed, it has been estimated in a number of regional catchments that denitrification in riparian wetlands stops 20%–60% of N coming from diffuse sources from entering the drainage network (Billen and Garnier, 2000; see Billen *et al.*, 2011, Chapter 13, this volume). At the landscape scale, the efficiency of riparian wetlands depends strongly on the hydrological setting (Haag and Kaupenjohann, 2001). However, it has to be borne in mind that such measure could give rise to pollution swapping (Butterbach-Bahl *et al.*, 2011, Chapter 6, this volume) due to possible enhanced $N_2O$ emissions.

Similarly, the introduction of extensive farm management such as set-aside grassland instead of intensive cropland in designated environmentally sensitive areas may be an efficient way to protect groundwater quality. This was successfully studied in Denmark by modelling (Dalgaard, 2009) and in France by practical application (*Vittel* mineral water protection area; Deffontaines *et al.*, 1994; Gras and Benoît, 1998).

### 11.2.4 Synthesis: relevance of the landscape scale for environmental and policy issues

As illustrated above, the principal issue concerning N at the landscape scale is the question of N transfer at short distance ($10^1$–$10^3$ m) by atmospheric or hydrological processes or by farm management transfer. The magnitude of this transfer is linked to the magnitude of the sources, the relative positions between sources and sinks, the heterogeneity of the landscape and the type of $N_r$ (e.g. $NH_3$ is generally deposited nearer the source than $NO_x$). Secondly, the landscape is composed of a range of ecosystems and anthropogenic systems (farmstead, roads, etc.) within which N cycling can be very different and which can have a large effect on the potential for N transformation and consequently lead to different $N_r$ budgets. Thirdly, in rural landscapes, farm management is a key component, as farming systems are by far the main source of $N_r$. Moreover, it is expected that the consequences of agricultural practices and the choice of farming systems may be very different according to the environmental conditions (climate, topography, soil types, proximity of sensitive areas).

These relationships determine the landscape function and highlight a dynamic view of what a landscape is (Leibowitz *et al.*, 2000). Any change in landscape structure will change the dynamics of N flows at field and landscape scales. This gives rise to questions such as: what are the consequences of N transfer on the production of $N_r$ or vice versa? What is the influence of landscape features on N transfer? And to what extent can farm management be adapted to landscape conditions to help mitigate the emissions of $N_r$?

This gives an insight into the possibility to adapt environmental policies to regional conditions. To some extent, the landscape scale is a very practical scale for researching solutions to N related problems as it considers both farming systems and environmental features. One practical application that is especially relevant at landscape scale is the protection of sensitive areas. Assessing the threat from nearby activities to these areas requires an estimation of the N flow from the source to the receptor, which itself requires knowledge of the patchwork of sources and sinks in and around the sensitive area, the intensity of agricultural activities, the features of nearby ecosystems and the conditions for atmospheric dispersion or N flow in the soil and aquatic systems.

## 11.3 Landscape description and functioning for N issues

### 11.3.1 Landscape characterization

#### Landscape scale

In all parts of the world, but more especially in Western Europe where the anthropogenic influence on the environment is large, a great variety of landscapes can be observed. This gives rise to the question of what distinguishes one landscape from another. Forman defined the landscape as follows in 1997: '*A landscape is a mosaic where the mix of local ecosystems or land uses is repeated in similar form over a kilometre-wide area. Within a landscape several attributes tend to be similar and repeated across the whole area, including geologic land forms, soil types, vegetation types, local faunas, natural disturbance regimes, land uses and human aggregation patterns. Thus a repeated cluster of spatial elements characterises a landscape*'. This highlights that, despite large small scale variability, there is a scale where some degree of homogeneity can be observed.

This implies a definition of the landscape scale, i.e. an area of several square kilometres. It could certainly be much larger in regions that are more uniform than in Europe. Defining the landscape scale for N issues, i.e. the transfer processes and farm management, a landscape consists of a repeated cluster of small catchments (typically several hectares to square kilometres each) for hydrological transfer, a repeated mosaic of ecosystems (including farmsteads) for atmospheric transfer, and several farms. Considering the spatial scale for atmospheric and hydrological processes (typically $10^1$–$10^3$ m) and the average size of farms in Europe ($10^1$–$10^2$ ha), the landscape scale can be considered to represent domains ranging from 1 km² to 100 km², with an interest in the spatial interactions within this domain, such as may occur on scales of a few metres to several kilometres. At this scale, it must be noted that all the landscapes elements are under the influence of the same climate and they may share a similar geomorphology.

#### Characterization of landscape elements

A first indicator characterizing the landscape is the relative area of the different land cover types related to the area of interest (Willems *et al.*, 2000). Sometimes this indicator is related to some specific landscape structure, e.g. the percentage of forest within a wetland (Vogt *et al.*, 2004) or the valley bottom. For linear structures, a similar rough approach is based on relative abundance measured as a density (length of a specific linear structure related to a specific area). Such indexes are well suited for large scales and allow us to describe the major trends at that scale. Nevertheless it does not account for the landscape heterogeneity and the spatial arrangement. The predictive power of such statistical approach fails in small catchments (less than 1–10 km²), suggesting that the spatial arrangement of landscape patches may become critical at these small scales (Strayer *et al.*, 2003).

Beyond the main mosaic of sources and sinks that characterize the landscape, several elements have a specific importance and can be described according to landscape functioning. They are represented in Figure 11.4 (Haag and Kaupenjohann 2001).

### Ecotones and corridors

These refer to the relation between ecosystems inside the landscape. The corridors determine the connectivity of the landscape. For N issues, they are areas within which there is a high rate of N transport, relative to the rate of change in the N transformations. The ecotones are ecological transition areas between two ecosystems (e.g. riparian zones between cropland and the river). There is a high rate of change in space in the nature of the N transformations (e.g. denitrification) among these areas.

### Hedgerows

This is one of the archetypal landscape elements that may influence the biophysical and ecological functioning of the whole landscape. A large diversity of hedgerow structures and densities can be observed in European countries. The recent introduction of field margin ecology in Europe (Marshall, 2002) highlighted the biophysical and ecological interest of hedgerows (Baudry *et al.*, 2000; McCollins, 2000) and showed their interest to consider the lateral transfer of N in the landscape.

### Hot spots and buffer zones

In hydrological systems, hot spots occur where flow paths meet substrates or other flow paths containing complementary or missing reactants. It might also occur in ecosystems where surface or subsurface conditions are different from the surroundings, promoting transformation processes (e.g. denitrification in grassed strips along rivers). They can also be related to deposition to sensitive ecosystems where critical loads can be exceeded due to the proximity of a strong source (Dragosits *et al.*, 2002; Loubet *et al.*, 2009) or changes in surface conditions (e.g. forest edge). When N retention or transformation is observed, these structures may also be called 'buffer zones'. These processes give them a specific function in the N cascade and potential for mitigation and they have become an important subject of research and a management tool for reducing pollution.

## Importance of the location of landscape elements

Because landscape elements clearly interact with the other structures of the environment, we need to take into account the precise location of these landscape elements relative to the sources and sinks of $N_r$. This specifically applies on the pathway of N pollutants along the transfer lines. Both hydrological and atmospheric transfer are concerned, the effectiveness of which might depend on transfer conditions, e.g. on groundwater depth or meteorological conditions. For example, a landscape structure such as a hedge will not have the same impact on N fluxes in a calcareous environment with deep groundwater level than the same hedge located on a soil with a shallow

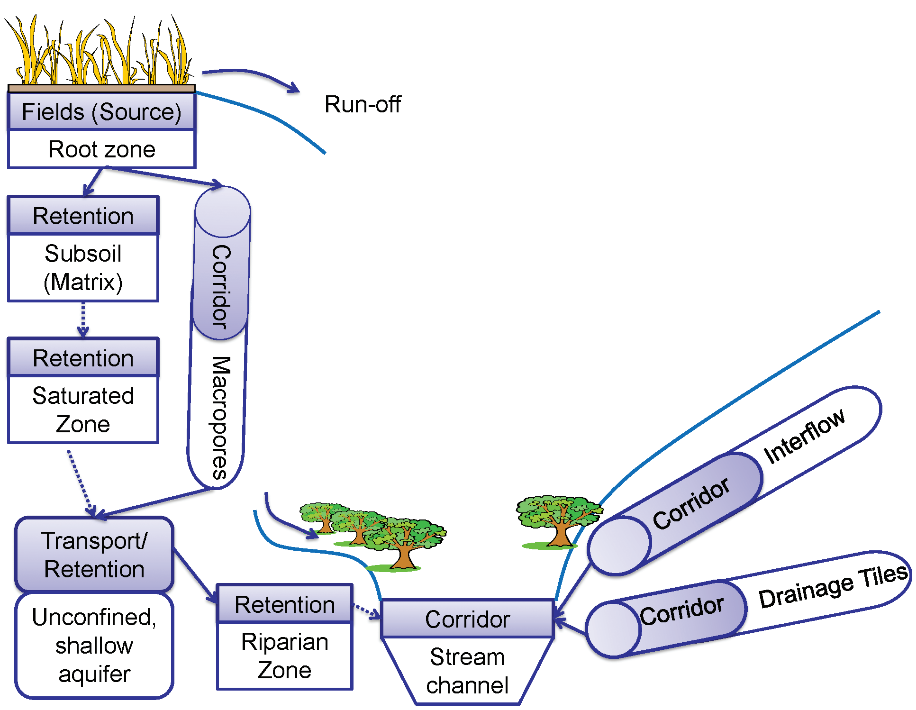


**Figure 11.4** Scheme of corridors and retention compartments. The sequence of compartments depends upon the specific hydrological setting and is spatio-temporally variable (redrawn from Haag and Kaupenjohann, 2001) with permission from Elsevier.

groundwater level. In the second case the ground flow goes through the superficial soil and the rooting zone, making it possible for ecosystem to capture $NO_3^-$ and for denitrification and subsequent $N_2O$ emissions to occur. Similarly, the effect of landscape structures like riparian buffer zones on N flows and transformation depends on their place within the catchment, up- or downstream (Mourier *et al.*, 2008). The same principles apply to atmospheric transport at a landscape scale. For example, the potential benefit of a wooded buffer zone for $NH_3$ dispersion will depend on the nature of the source and the location, dimensions and structure of woodland, as well as the location of the receptor area to be protected. All this clearly indicates that the spatial location of all landscape elements must be explicitly accounted for in landscape description and modelling.

### 11.3.2 Interactions between farming systems and landscape structure

#### Spatial organization of crop mosaic and farm practices

Rural landscapes result from the aggregation of multiple farms and their relationship with other land uses. The location of the farmsteads (more or less dispersed) play a significant role in the design of landscape patterns. Within a single agricultural region, landscape pattern results to a large extent from decisions made at the farm level and how the farming systems integrate at landscape level (Deffontaines *et al.*, 1995). Firstly, farming systems control the composition of the landscape mosaic in terms of surface area used for agricultural production (arable fields, grasslands). Secondly, for a given farming system, crop allocation to the fields is controlled by the combination of agronomic constraints for crop succession (Colbach *et al.*, 1997), environment constraints, soil quality (Stockle *et al.*, 2003), and specific constraints of the farm field pattern, including accessibility, field size, distance to farmstead (Thenail and Baudry, 2004; Rounsevell *et al.*, 2003), and market forces (e.g. quotas, market prices). The relative balance and hierarchy between the constraints mentioned above, differ among the farming systems. Thenail (2002) has emphasized the strong spatial pattern of the crop mosaic of dairy farms in north-eastern Brittany (western France), which is to a large extent determined by distance to farmstead. Land use is organized into approximate concentric circles around the farmstead (Figure 11.5): pastures grazed by dairy cows are located as close to the farmstead as possible, because dairy cows move daily from the farmstead into the fields. A second circle consists of fields used for crops and forage. The outer circle consists of permanent grasslands grazed by heifers, extensive lands or woodlands, which require little management. This applies to many locations in north-western Europe. By contrast, crop allocation in crop farming systems or intensive breeding farming systems are expected to be less controlled by the distance to farmstead. More generally, the degree of spatial specialization varies according to the farming systems, the diversity of crop rotations and the specific constraints of the farm.

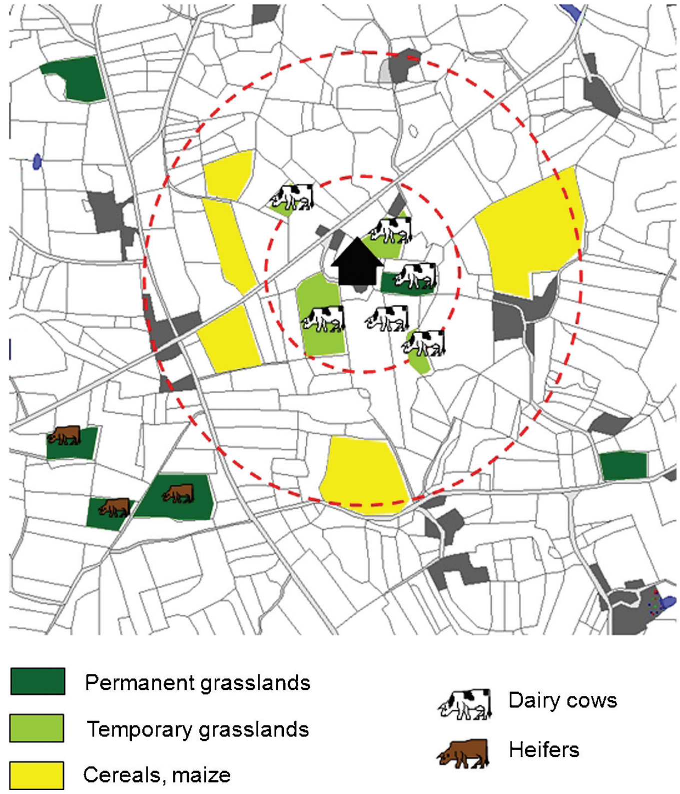


**Figure 11.5** Theoretical organization of the crop mosaic according to the distance to the farmstead in dairy farms in Brittany (western France) (redrafted from Thenail and Bandry, 2002). With permission from Elsevier.

#### Interactions between farming systems and the semi-natural landscape elements

Strong interactions exist between farming systems, the crop/grassland mosaic, and the pattern of semi-natural, often perennial, landscape elements such as those located on the field margins (grass strips, hedges, ditches, woodland plot, wetlands, etc.). Thenail and Baudry (2004) found different degrees of land-use allocation in farms depending on the hedgerow density: the presence of hedgerows distorts to a certain extent the concentric pattern of crop allocation described above in dairy farms.

In Jutland (Denmark), Kristensen *et al.* (2001) showed that the management of hedgerows, woodlands, and permanent grasslands varies according to the type of farming systems. Thenail and Baudry (2005) have focused on the management of small riparian wetlands and their interaction with farming systems. In the example of dairy farms in Brittany (western France, see, for example, Figure 11.5) where riparian wetlands form a large part of the farm area and are located close to the farmstead, they are intensively used for animal grazing or fodder. On the contrary, where they represent a small part of the farm area, or where they are far away from the farmstead, they tend to be abandoned by the farmers.

## 11.4 N transfer and transformation processes from the plot to the landscape scale

Detailed descriptions of N processing in terrestrial, freshwater and atmospheric systems are presented in Butterbach-Bahl *et al.*, 2011; Durand *et al.*, 2011; Hertel *et al.*, 2011 (Chapters 6, 7 and 9 this volume). N transfers at the farm scale are described in Jarvis *et al.* (2011, Chapter 10, this volume). In this section we specifically highlight the ecosystem, hydrological and atmospheric processes that contribute most to interactions and modify fluxes and budgets at the landscape scale.

## 11.4.1 N processes at ecosystem scale

The landscape scale is first characterized by a variety of interlinked ecosystems of varying sizes. In cropland and some grassland, the large inputs of mineral fertilizer create a much larger pool of $N_r$ than in natural ecosystems. A key question at landscape scale is that of the spatial transfer of N from eutrophic to oligotrophic ecosystems, leading to N impacts in the latter. Consequently, there should be a special focus on the understanding of environmental conditions and C–N turnover and transformation in these ecosystems with low direct N input but significant indirect N input through lateral transfers (e.g. wetlands, forests, grass strips). This means that the N turnover in the soil and vegetation (litter, dead leaves) have higher relevance than in agro-ecosystems with high direct N input (see Butterbach-Bahl *et al.*, 2011, Chapter 6 this volume).

It is also necessary to better understand and quantify the processes of N capture in these oligotrophic ecosystems, from both the atmosphere (dry and wet deposition) and the soil water (uptake from the groundwater to the biogeochemically active upper soil layers). In the former, $NH_3$ and $NO_2$ absorption by stomata (including compensation point modelling) and further recycling in the plant metabolism must be considered, as well as N capture by the leaf surface and subsequent transfer to the soil surface by rain washing (Hertel *et al.*, 2011, Chapter 9, this volume). For this, a minimum description of the canopy structure (height, leaf area density, etc.) is essential. In the latter, an understanding is needed of the rooting depth, groundwater depth and the water transfer in the soil and nutrient absorption by roots under conditions close to saturation and anoxia (Beaujouan *et al.*, 2001; Durand *et al.*, 2011, Chapter 7 this volume).

## 11.4.2 Vertical and lateral transport processes

### Surface and deep hydrology

Water transport in the natural environment can be roughly separated into vertical flow (e.g. water infiltration from the surface to groundwater) and lateral flow (surface runoff, subsurface and deep lateral flow, base flow) (Cirmo and McDonnell, 1997). For landscape analysis, two types of catchment are generally considered: shallow groundwater catchments, in which the vertical flow feeds into the subsurface lateral flow, and deep groundwater watersheds (e.g. karst situations) with deep vertical flow. In the first case, surface hydrology can lead to significant redistribution of N that feeds into the N cascade and modifies $N_r$ fluxes and budgets. In the second case, hydrology generally does not create significant interactions at the landscape scale. In the majority of situations, the relative importance of shallow and deep water pathways varies rapidly in space and time. These pathways have very different time scales (minutes to hours/days for surface flow, months to years/decades for deep flow), resulting in complex patterns of residence times and seasonal variations. A consequence is that the fate of the N applied in a catchment and its impact on stream water quality, which is always a mixture of waters with contrasting histories (Boehlke and Denver, 1995; Durand and Juan Torres, 1996), will depend on the location of its application within the catchment and on the landscape structure.

Some specific events can occur at some places in the landscape. In areas with an impermeable layer close to the soil base, a significant lateral flow can occur beneath or in the soil, with consequences for N transport (Molenat *et al.*, 2008). In some places such as wetlands, the surface water–groundwater interaction (Dahm *et al.*, 1998) might be very important for N capture by vegetation and subsequent possible denitrification. This might be important for $N_2O$ and $NO_3^-$ budgets at landscape scale and it is therefore an issue in landscape modelling (Beaujouan *et al.*, 2001). As a whole, due mainly to differences in local water balance and pathways, $NO_3^-$ leaching is larger at points further down the slope, and denitrification and plant recapture is more important downhill. Consequently the interactions between ecosystems could require more attention in the valleys, e.g. at the wetlands–arable land/grassland interface.

### Atmospheric transfer

In rural landscapes, emissions of $N_r$ into the atmosphere are predominantly the result of agricultural activities. In these landscapes, mainly $NH_3$, but also $N_2O$ and N oxides are emitted from livestock housing, the storage of manures and slurries and the application of organic and inorganic fertilizers to fields. Some of these gases are also emitted, to a much lesser extent, from mobile agricultural sources (trucks, tractors, etc.). Although $N_2O$ emissions can be strongly affected by landscape structure, once emitted, $N_2O$ does not interact significantly with the landscape. Similarly, although atmospheric $NO_x$ concentrations can vary substantially across landscape, the dry deposition velocities of $NO_2$ are small, so that it generally has only a small influence on local spatial patterns of total $N_r$ deposition. By contrast, $NH_3$ dispersion and deposition is very important for processes at the landscape scale because it is both subject to relatively large local emission variations (farmstead, field) and high dry deposition velocities. Therefore high atmospheric concentrations and large deposition rates can occur close to the source (Fowler *et al.*, 1998; Van Pul *et al.*, 2008; Dragosits *et al.*, 2002). Uncertainty analysis shows that most of the uncertainty in predicting the fate of atmospheric $NH_3$ is due to the uncertainty in deposition processes (Loubet *et al.*, 2009), including compensation points.

## 11.4.3 Transfer linked to farm activity

As mentioned above, farm activity is by far the main source of $N_r$ either in mineral or organic form in European rural landscapes. Large amounts of organic matter, and hence

N, are manipulated by farm operations (manure, harvest). Moreover, crop fertilization and animal feed often result in a large import of N to the farm, which is distributed within the landscape according to farm management. In contrast, crop harvest and animal production lead to exports from the farm and landscape. The magnitude of these N transfers and their organization depend on the farming system and farmer's decision making. They are described in more detail in Jarvis *et al.* (2011, Chapter 10 this volume). The location of the crops and grasslands relative to the other ecosystems, as well as animal displacement, also depend to a large extent on the farming system.

### 11.4.4 Anthropogenic modifications of transport processes

Anthropogenic structures and activities such as urban areas, transport pathways (roads, tracks, canals) or agriculture modify the natural pathway of water in most places in Europe. In agricultural land, some specific modifications can influence N flows at different scales.

- Ploughing (plough layer) and soil compaction by large machinery (Lipiec and Pniewski, 1995) has a large effect on water infiltration and might increase surface lateral flow and modify the local hydrology and related N flows.
- High density ditch drainage systems have traditionally existed in most European landscapes for centuries and tile drainage has also been set up in recent decades. Both have a strong impact on lateral flows of water and dissolved N and hence modify the transfer time of water as well as spatial relationships between ecosystems. They have significant effects on $NO_3^-$ leaching (Dinnes *et al.*, 2002) and $N_2O$ emissions (Reay *et al.*, 2003).
- As already mentioned, the presence of woodland and hedgerows in a landscape increase the surface roughness and hence the atmospheric dispersion. Moreover, patchiness increases the number of hot-spots in local deposition, as deposition is the largest at transition zones such as forest edges (Loubet *et al.*, 2009).
- Constructed wetlands are implemented in many countries because they have the potential for reducing $NO_3^-$ contamination from agricultural areas (Spieles and Mitsch, 2000, Woltemade, 2000; Tanner *et al.*, 2003). However, there is suspicion that they may emit significant amounts of $N_2O$ and $CH_4$ (Sovik *et al.*, 2006). It is thus of utmost importance to study these features in close relation with studies that are performed on natural wetlands.

### 11.4.5 Conclusion on landscape N transfer and transformation processes

It is necessary to combine knowledge of the spatial distribution and extent of N sources with knowledge of the pathways connecting those sources with adjacent aquatic or terrestrial ecosystems, in order to understand the relationship between anthropogenic sources and natural receptors. This is also necessary to both predict the impact of changing land use and management on N fluxes and budgets at plot (as a source) and landscape scale. This requires an improvement of our understanding of some anthropogenic drivers (e.g. water/N flows from farmsteads, transfer through ditch networks) and of some specific processes in natural ecosystems (e.g. recapture and transformation of N – coming from upslope – by soil and vegetation in wetlands).

As mentioned before, all the relevant processes at landscape scale have similar space scales, between several metres and several kilometres, but the frame is different according to the type of transfer. For hydrological transfer, the catchment is obviously the relevant scale, with the watershed limits – where a nil flux condition can generally be applied – giving the boundaries of the domain. Such limits and conditions do not exist for atmospheric transfers. The simulation domain is often a square and it is necessary to prescribe boundary conditions from measurements or from a higher scale model. For farm activities, the domain consists of the farmstead and the fields and naturals areas depending on the farm. It is a discontinuous domain with some of the fields possibly outside the studied landscape. Conversely some parts of the landscape can be attached to farmsteads outside the landscape. This mismatch between the domains for the different types of transfer makes it difficult to have a unified approach in investigating landscape from an N perspective. Nevertheless the consistency between space scales is a facilitating factor.

Considering the time scales, the range is much larger. The farm scale processes are event-based and proceed along the crop cycle, the animal breeding cycle or the year. The natural processes can be very short (seconds to minutes) like $NH_3$ deposition close to a farm building or surface run-off during a heavy rain, or very long. The latter is the case of hydrological transfer which can last several years or decades between the rainfall and the exit at the catchment outlet. As a whole, at landscape scale, atmospheric processes have short time scales (seconds to day) and hydrological transfer have much longer time scales, from days to years. Consequently, it is difficult to establish relationships between N inputs and outputs from a given landscape and to assess budgets at landscape scale both from experimental and modelling points of view, unless working on the long term.

## 11.5 Landscape modelling of N

Although measurements have been made of N flows between individual landscape elements such as the transfer of atmospheric $NH_3$ from a source to downwind vegetation (see Loubet *et al.*, 2009; Theobald *et al.*, 2001) or N flows along drainage or stream networks (see Boehlke and Denver, 1995; Dahm *et al.*, 1998; Molenat *et al.*, 2008). N flows within and across entire landscapes are still beyond the capabilities of current technology or research budgets. For example, remote sensing can be used to study the spatial distribution of atmospheric $NH_3$ (Clarisse *et al.*, 2009) but the current horizontal and vertical resolution of this technique is not adequate for the landscape scale. The simultaneous measurement of the flows and interactions of multiple $N_r$ species through multiple media (atmospheric, hydrological and plant and soil systems) would require a complex network of sensors and a large amount of researcher time. Moreover, interpreting these measurements requires knowledge of the agricultural practices at field and farms scale all over the studied landscape and its surroundings. This might apply for several years, due to the time scales of $N_r$ transfer. This type of experimental approach is currently beyond the capabilities of most research projects. This is one of the main reasons why the use of process modelling approaches seems to be the way forward to study landscape N flows and budgets. However, field data are still required to verify model predictions although measurements at a lower resolution (both spatially and temporally) can be used for this.

Landscape modelling of N extends the process modelling approach of single component fluxes (e.g. emission/deposition/leaching) to follow N from source through the different compartments of a study landscape with multiple routes in the N cascade (including hydrology, atmosphere and farm management). By contrast to plot-scale modelling, landscape modelling focuses on spatial transport and transformation, both within and between the compartments of the landscape. Comprehensive landscape models must therefore take into account the nature, location and size of the emission sources, the distribution of land cover within the landscape, the hydrology, the meteorological conditions, etc. It should also account for transformation of N within the different components of the landscape. This approach requires a clear understanding of all landscape compartments, as well as the boundaries between them, and how $N_r$ transfers across these boundaries. It also requires that attention be given to hot-spots of N emissions, which are the drivers of a large proportion of N transfer, as well as to more diffuse sources. Recycled fluxes in the cascade must also be considered, such as the fate of atmospherically deposited N, which is an important driver of impacts and further feeds the N cascade. Defining compartment boundaries between model domains is not trivial, because of the contrasting needs of the different model components. For example, the boundaries relevant for hydrological transfer (watershed) have no or little relevance for atmospheric transfer or anthropogenic farm transfer. Landscape models need to be appropriately calibrated and verified, which may use both spatial and temporal datasets.

This section focuses on detailed comprehensive models and their ability to identify the main issues and investigate the relevance of some policy measures. However, these models can also provide the basis for setting up simpler models, i.e. dealing with a limited number of processes and/or considering simplified formulations of transfer and transformation processes. These models can be also be used to develop and support landscape management decisions.

## 11.5.1 Key issues for comprehensive landscape modelling of N

To be able to model the main interactions within a landscape, **detailed input data** are needed for a large number of landscape elements, such as individual fields, livestock buildings, patches of woodland, hedgerows, streams, etc. These input data include properties such as soil type, building height, building ventilation rates as well as management activities related to farming, such as the application of mineral fertilizer or livestock manures, planting/sowing/harvesting of crops, and grazing/housing of livestock. While average conditions and activity data may be adequate for regional scale modelling, real world **farm management data** are required to understand the flows of N in a specific landscape, as well as diurnal/seasonal/inter-annual variability. The input data should also have **sufficient spatial resolution** to consider small spatial elements (e.g. hedgerows, grassed strips) that are relevant for landscape processes. Environmental variables, such as temperature, precipitation, wind speed/direction, solar radiation, etc., are also required.

However, the different components of a landscape model do not need to be as detailed as a single-compartment model (i.e. ecosystem, atmospheric, hydrological, farm model), where processes are investigated in greater detail. Moreover, while process models tend to focus on particular compounds ($NH_3$, $N_2O$, $NO_3^-$, etc.) and particular aspects of the N cycle (e.g. atmospheric transport modelling; catchment modelling, crop or grassland modelling), a landscape model needs to bind all these components together. One challenge in landscape modelling is thus to achieve the right balance between describing the details of the individual processes and ensuring consistency between the different models.

An essential requirement for landscape modelling is that all elements and activities are assigned to a **spatial location**, i.e. a map location is recorded, and a spatial database developed, which provides input data for the model. It should be noted that, despite the assumed importance of corridors in transfers at landscape scale, these processes are generally not accounted for in landscape models. This is because it would generally require a very high spatial resolution (e.g. for a ditch network) and the processes are not yet well quantified. For N transfers in rural landscapes, such corridors are mainly relevant for farm transport of fertilizers, feed and products, and for riverine fluxes, which can be specified by the models.

For practical application of landscape processes in regional models, it is not realistic to collect and use detailed field and farm input data. For this reason, landscape models are tested, for example landscapes where detailed datasets are collected. This means that for upscaling the findings of landscape models to the regional level, there is a need to generalize the processes and consequences, as well as to determine landscape typologies, based on global indicators for landscape structure and farming systems. Typologies could be derived from e.g. remote sensing data, vegetation and topography maps and regional agricultural censuses. At present, such indicators are still to be defined and their relevance assessed.

## 11.5.2 Examples of landscape scale models for N

Over the past few years, a number of modelling assessments have been carried out at the landscape scale. From a historical point of view, landscape modelling of N may be seen as a logical extension from the separate fields of interest in stream and groundwater flows of $NO_3^-$ and in local scale atmospheric transport and deposition modelling of $NH_3$ and $NO_x$. In integrating these different elements, the approach must also account for ecosystem processes and be placed in the context of farm management. Current models have been developed with a focus on environmental science disciplines (hydrology, atmospheric sciences, farming system) or environmental issues (impacts on water quality, air pollution, sensitive ecosystems).

### Modelling flux heterogeneity at the landscape scale

The model *Initiator2* (Integrated Nutrient ImpacT Assessment Tool On a Regional scale; De Vries *et al.*, 2005) simulates (i) emissions of $NH_3$ and greenhouse gases ($CO_2$, $CH_4$ and $N_2O$) from animal housing systems and agricultural soils and (ii) leaching and runoff of nutrients (specifically N and phosphorus) from agricultural soils to groundwater and surface water. In this approach, the modelled $NH_3$ emissions from fields and housing systems form the input to an atmospheric transport model (OPS; Van Jaarsveld, 1995), which is used to assess the N deposition to agricultural and non-agricultural systems using a grid resolution of 250 m. Initiator2 was used to make an integrated assessment of the present environmental status (year 2004) of the Noardlike Fryske Wâlden area (NFW) in the north of the Netherlands and of impacts of management measures that are being applied in the area (Figure 11.6). The input database contained animal numbers, agricultural practices and land management, such as manure application techniques for each farm in the NFW area, based on results from questionnaires from the Dutch Central Bureau on Statistics. This database was linked to detailed topographic data, spatially explicit soil data (soil map 1: 50.000) and hydrology (Kros *et al.*, 2007).

The results of the analysis for the NFW give an insight into the high spatial heterogeneity in $NH_3$ and $N_2O$ emissions as well as in the $NO_3^-$ concentration in upper groundwater. In almost 6% of the area the EC $NO_3^-$ groundwater limit of 50 mg $l^{-1}$ was exceeded, even though for the NFW area as a whole, the average $NO_3^-$ concentration was only 10 mg $NO_3$ $l^{-1}$. The map of $N_2O$ fluxes (Figure 11.6b) shows larger emissions for wet/peaty locations, in contrast to the map of $NO_3^-$ concentrations (Figure 11.6c), where the values are largest for dry/sandy locations. However, this type of model cannot capture the lateral spatial interactions at the landscape scale, as it does not simulate small scale (i.e. 10–100 m) atmospheric and hydrological processes.

### Modelling N interactions at the landscape scale

A number of modelling studies have recently been carried out to address spatial N interactions at the landscape scale, including farm management. In the following paragraphs, examples of different approaches for landscape modelling are briefly reviewed. The focus is not on the technical aspects of the individual models, but on how the flows and transformations of N are represented, and the insights gained from working at this scale.

The UK *LANAS integrated model* (Landscape Analysis of Nitrogen and Abatement Strategies) is centred around atmosphere, ecosystem and soil interactions, with leaching only included as an end point, i.e. vertical or horizontal underground/in-stream flows of N are not represented (Theobald *et al.*, 2004; Dragosits *et al.*, 2005). The LANAS model consists of established process-based models for the main components of the landscape, NGauge (used at field scale for grassland systems, Scholefield *et al.*, 1991), SUNDIAL (crop systems, Smith *et al.*, 1996), and LADD (atmosphere, Hill 1998; Dragosits *et al.*, 2002). These models and a simple farmstead model, FYNE (Theobald *et al.*, 2004), were coupled via a 'wrapper' programme to control the data exchanges through a spatial database which stores, sends and receives input and output to/from the component models during simulation. Vertical and horizontal flows are only fully represented in the atmosphere component of the landscape, with the field models acting as plot models for each of the grass/crop fields in the landscape. Output from the LANAS model at the landscape scale includes $NH_3$ and nitrous oxide emissions, dry deposition of $NH_3$ and leaching of $NO_3^-$ out of the bottom of the ecosystem models. An example of LANAS output is given in Figure 11.9.

The Danish *ARLAS project* (Dalgaard *et al.*, 2002; Hutchings *et al.*, 2004) focussed on farms, ecosystems and effects of N management on drinking water boreholes in an area of central Jutland (Denmark). The model developed under the ARLAS project did not include an atmospheric component model, so that emissions of $NH_3$ to the atmosphere were not dispersed or deposited during the model simulation. The groundwater and hydrological component was of central interest in the project, which analysed how the water quality could be improved by restricting N losses from agricultural sources. The main aim of the model application was scenario testing, including the estimation of N-surpluses from organic farming (Dalgaard *et al.*, 2002). Similarly, the introduction of extensive farm management such as set-aside grassland instead of intensive cropland in designated environmentally sensitive areas was shown to be an efficient way to protect groundwater quality (see Figure 11.7; Dalgaard, 2009). This illustrates the practical nature of landscape scale modelling with its emphasis on local sources, sinks and flows of N.

The French *EcoSpace project* (Beaujouan *et al.*, 2001) coupled a hydrological model (TNT, based on TOPMODEL, Beven and Kirkby, 1979; Beven, 1997) with an existing generic crop model (STICS, Brisson *et al.*, 1998). The two models were coupled with the 'soil store' for N and water being controlled by STICS, and the 'drainage store' being controlled by TNT. An atmospheric model was developed to account for deposition to ecosystems close to farmsteads or slurry application, but it was not fully coupled to the STICS/TNT model. An example of the model output is given in Figure 11.3. The main aim of the study was to investigate mitigation options for the improvement of stream and surface water quality, and in particular to minimize N pollution. Beaujouan *et al.* (2001) used the model to evaluate the influence of the spatial distribution and size of patches of crops in six theoretical agricultural catchments of different types and shapes (convergent/parallel/intermediate catchments with either concave or convex

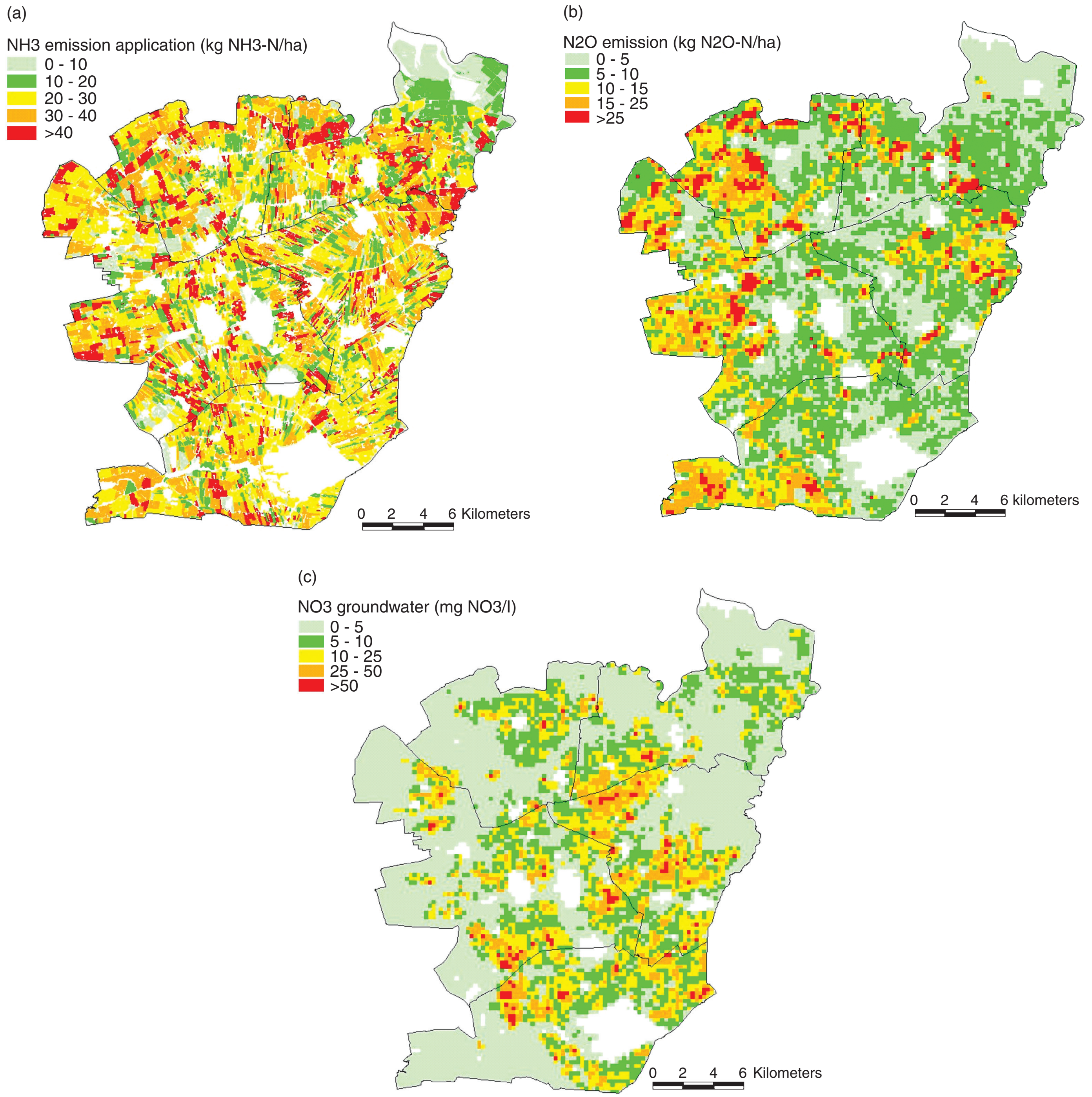


**Figure 11.6** Maps calculated using Initiator2 for the NFW region in the Netherlands for 2004: (a) annual $NH_3$ emissions from manure application; (b) total annual $N_2O$ emissions; (c) nitrate concentrations in the upper groundwater (from Kros *et al*., 2007).

slopes). In the scenarios, source areas were placed upstream or downstream of sink areas, as well as spread in checkerboard patterns throughout the catchments. When applied to real cases, the model output compared favourably with real catchments in Brittany (NW France).

More recently, a consortium of European research groups has started an ambitious project on landscape analysis of N interactions, as a component of the EU *NitroEurope Integrated Project* (see also www.nitroeurope.eu; Sutton *et al*., 2007). One of the aims of the landscape component of the project is the joint development of an integrated landscape scale model, *NitroScape*, to simulate the flows of N between all components of rural landscapes. The NitroScape model is a framework coupling suitable existing component models for the atmosphere, ecosystems and hydrological components, as well as farm scale processes, with a spatial database (Cellier *et al*., 2006; S. Duretz, personal communication, 2010) (Figure 11.8). The approach is similar to the one used in the LANAS project described above, but with a more sophisticated model coupler, which allows interaction between the component models

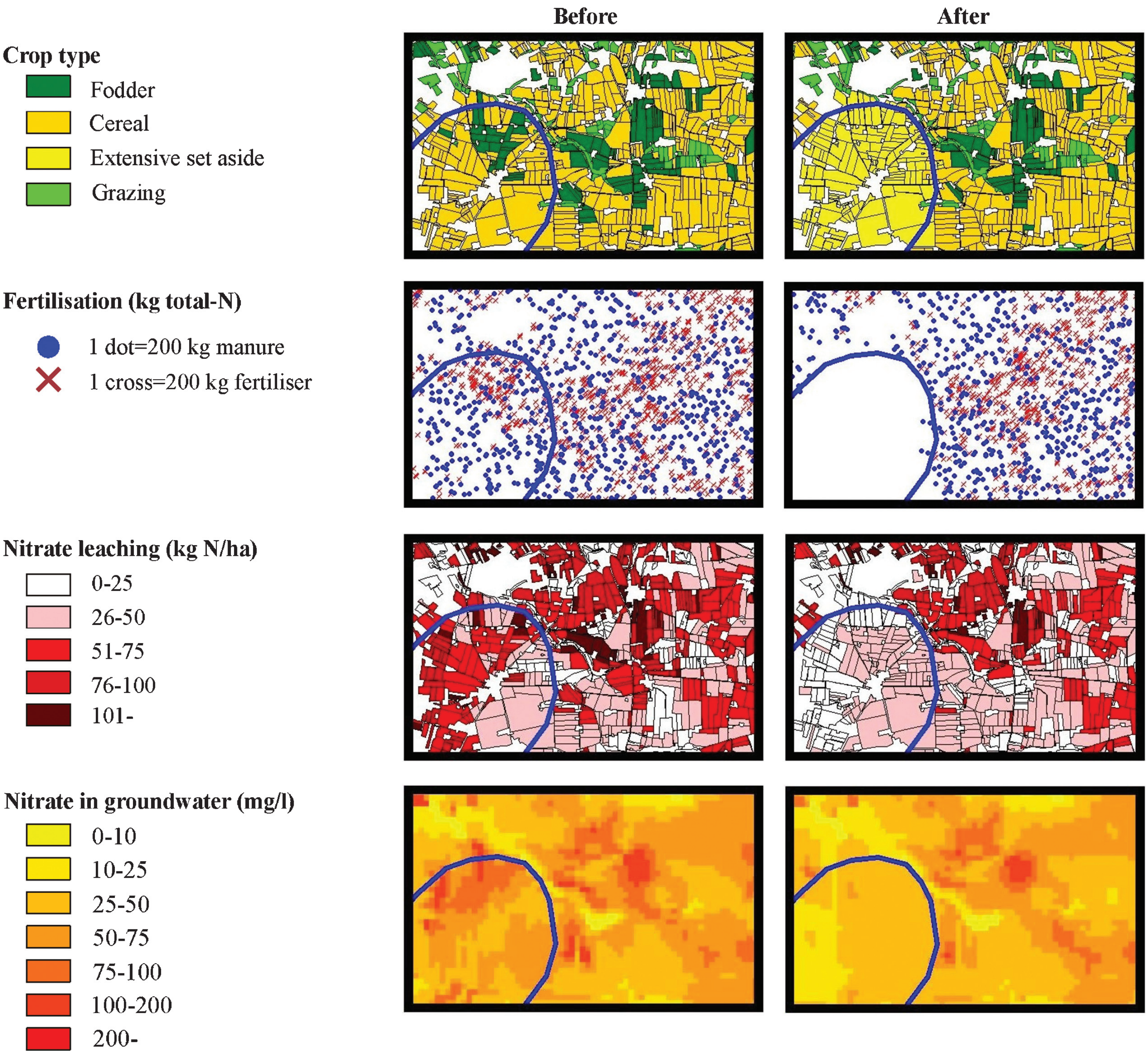


**Figure 11.7** Modelled example of landscape scale mitigation of nitrate leaching via the introduction of non-N-fertilized set aside grassland in a drinking water borehole catchment (boundaries in blue line), situated in the Tyrebæk stream watershed, Central Jutland, Denmark. The 'before' and 'after' maps show results from crop rotation, manure, farm and hydro-geological models, before and after introducing extensive farming systems in the borehole catchment (after Hutchings *et al.*, 2004; Dalgaard, 2009) with permission.

during run-time and minimum adaptation of existing models. NitroScape will consider the majority of the components of N transfer at landscape scale. It will be tested and verified over a range of rural landscapes under different climatic conditions, with different farming systems including livestock. Each landscape has a specific topic and includes natural areas where impacts of N can be predicted.

### 11.5.3 Conclusion on landscape modelling

Progress has been made by a number of recent and current studies exploring landscape scale modelling from different starting points and for different purposes, whether to investigate strategies for the provision of clean drinking water or to protect sensitive semi-natural areas from excess atmospheric N deposition. This required the consideration of both natural and anthropogenic processes and modelling them with sufficient levels of detail in a spatial context. A clear challenge emerges of how to implement the interaction between different component models, using the right tools. These models have also improved the understanding of the relative importance of transfer and transformation processes in rural landscapes. However, there is still much to learn about the interactions of the different elements in the landscape and the development of new models can help with this.

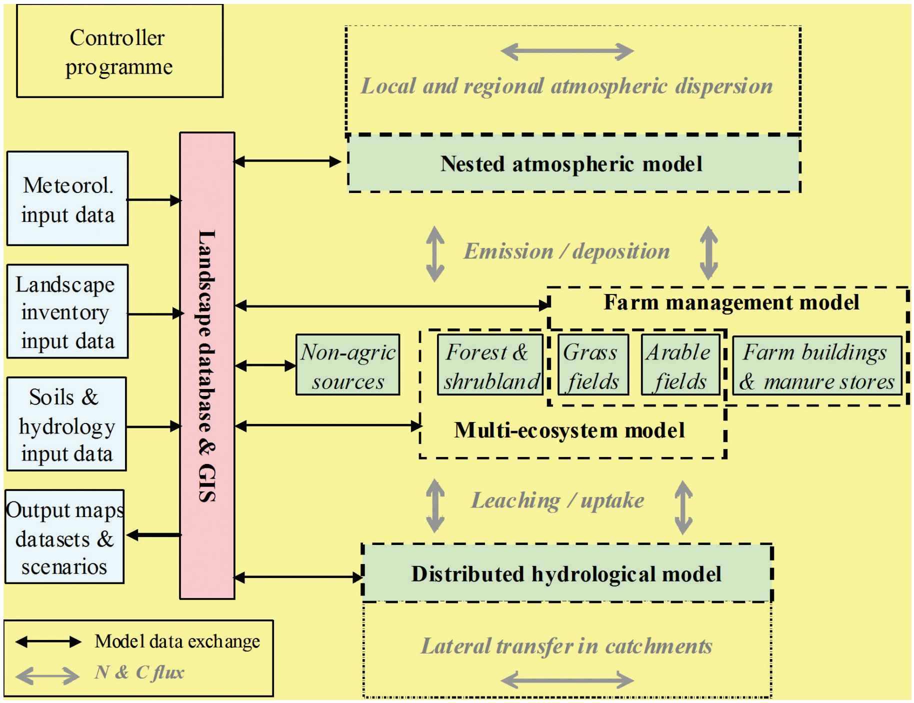


**Figure 11.8** Schematic of the NitroScape modelling framework to provide a fully integrated treatment of N exchange fluxes at the landscape scale. The landscape is envisaged as integrating farms, fields, semi-natural land and non-agricultural sources, with lateral and vertical dispersion fluxes through the atmosphere and hydrosphere (from Sutton *et al.*, 2007).

## 11.6 The importance of integrating the landscape perspective into N assessment and management

### 11.6.1 N mitigation at the landscape scale

The following examples of land use management, often referred to as 'spatial abatement' or 'spatial planning' (Bleeker and Erisman, 1998; Lekkerkerk, 1998; Theobald *et al.*, 2001; Sutton *et al.*, 2004; Dragosits *et al.*, 2006; Schou *et al.*, 2006) highlight the relevance of the landscape scale for mitigating N impacts on the environment.

- **Establishing tree belts** around $NH_3$ sources (e.g. animal housing) or sensitive areas has been suggested as an efficient tool to diminish deposition to sensitive ecosystems and could be used as a tool for their protection (Sutton *et al.*, 2004; Dragosits *et al.*, 2006).
- **Constructing wetlands** or more generally restoration and management of wetlands (Haycock *et al.*, 1997; Woltemade, 2000; Tanner *et al.*, 2003; Viaud *et al.*, 2004) have proved to significantly decrease the $NO_3^-$ concentration in surface waters and thus are an efficient buffering element, protecting the river course from the impact of N (Haycock *et al.*, 1997; Viaud *et al.*, 2004). This has led eco-engineers to the implementation of constructed wetlands for water quality objectives. It is typically a landscape issue because their efficacy and their management depend on the catchment (including hydrological functioning, hedgerow network and grassed strips) that contains the wetlands and on the farming systems (Haycock *et al.*, 1997).
- **On-farm spatial planning** provides means to help protect sensitive areas by locating certain activities in the most suitable location. This can include locating farmsteads, crops and grasslands, as well as high emission activities, such as manure spreading to locations that reduce emissions and/or impacts of the emissions. Such strategies can also help protect fresh water by decreasing $NO_3^-$ leaching and groundwater contamination (see Figure 11.7; Dalgaard, 2009; Deffontaines *et al.*, 1994), as well as help protect sensitive ecosystems such as *Natura 2000* sites from $NH_3$ deposition. For example, Dragosits *et al.* (2005) modelled the effect of burning poultry manure for power generation (instead of spreading it on fields) or moving poultry houses away from a nature reserve on $NH_3$ and $N_2O$ emission, N deposition (Figure 11.9) and $NO_3^-$ leaching. These measures can exploit spatial relationships to reduce emissions (e.g. arranging activities to reduce $N_2O$ emissions) as well as use the source–sink relationship to decrease local impacts of $NH_3$ on sensitive ecosystems (Loubet *et al.*, 2009). These approaches can be considered as extending the vision of 'precision farming' from the field to the landscape scale.

In all cases, practitioners are faced by the complexity of the landscape because it involves not only the studied system (wetlands, tree belt, etc.), but also the surrounding landscape. Modifying crop spatial allocation needs to consider the whole farming system for consistency and its interactions with the landscape. All these measures, therefore, must be placed in a landscape perspective and consider long-term interactions.

### 11.6.2 Using landscape-scale interactions to improve regional models

Air pollution or climate models at regional or national scale often use a grid size of between 5 × 5 km² and 50 × 50 km², limiting simulations of atmospheric concentration or deposition

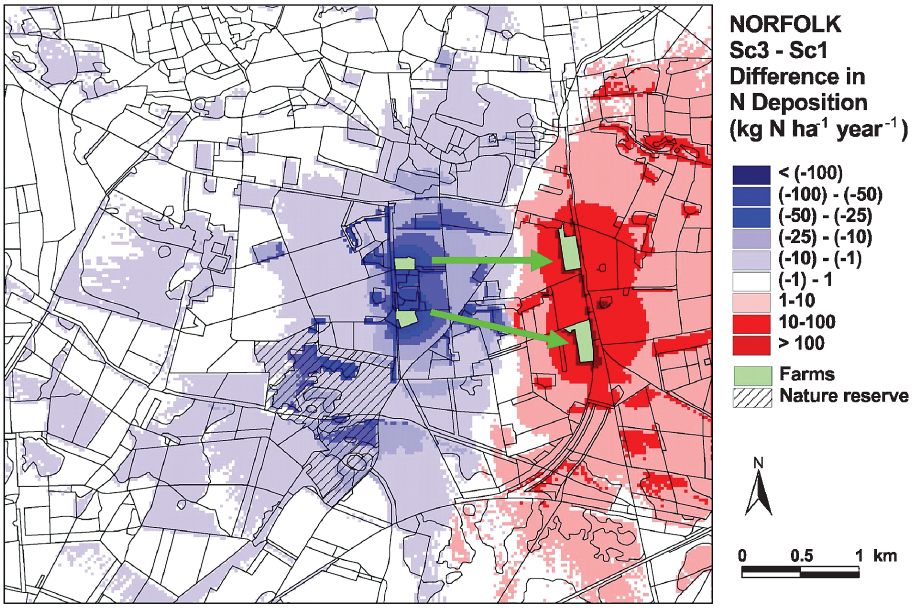


**Figure 11.9** Difference in N deposition ($NH_3$ dry deposition) due to moving of poultry from two sets of buildings in the immediate vicinity of a nature reserve (hatched area) to a more distant location (approx. 1.5 km east/right) (from Dragosits *et al.*, 2005). With permission from Elsevier.

to this resolution. In reality, atmospheric deposition of N, especially $NH_3$ dry deposition, can vary by several orders of magnitude within a grid square of a national or regional model (Dragosits *et al.*, 2002). This variability is mainly due to the localized nature of $NH_3$ emission sources and the high dry deposition velocity for $NH_3$ for semi-natural vegetation (sinks). Using data from a regional model could, therefore, significantly underestimate (or overestimate) the environmental impacts since the actual deposition at a particular location could be much higher (or lower) than the model simulation. Landscape-scale atmospheric models can take into account the sub-grid short-scale interactions between sources and sinks and should therefore be used to better assess the uncertainty of national or regional models by estimating the statistical distribution of deposition values within the grid square. This would help to assess local deposition and impacts on conservation areas at a regional scale (see e.g. Loubet *et al.*, 2009; Hertel *et al.*, 2009).

Similarly, in regional scale water quality models, diffuse sources of nutrients from agricultural areas are most often estimated either from empirically determined export coefficients or from an additive approach based on the output of separately run plant/soil/water models at the plot scale. In the best case, they use an arbitrary reduction coefficient accounting for 'landscape' or 'riparian' retention (see e.g. Billen *et al.*, 2009). None of these approaches are able to simulate the effect of changes in the spatial structure or functioning at the landscape scale. Landscape-scale transfer models can help draw a more complete picture by quantifying the storage/release of N pools in soils and groundwater, which are, *per se*, an important issue for N management, and by describing the intra-annual dynamics of the N delivery to the streams. These models are also better suited to complex scenario analyses, especially to quantify the effects of management practices on N losses. Such results could be aggregated as input to larger scale models, based on the catchment/subcatchment aggregation.

### 11.6.3 Role of the landscape scale in environmental N policy measures

A number of policies and measures in the EU and various Member States (see Oenema *et al.*, 2011, Chapter 4 this volume) address the importance of landscape structure and functions in relation to N. The potential for considering the landscape scale in these policies depends in part on the level of detail that can be used by Member States to implement them.

- **Water related policies** (Water Framework Directive, Nitrates Directive, Urban Waste Water Directive and Groundwater Directive): the Water Framework Directive applies a river basin and a catchment approach, while the Nitrates Directive distinguishes Nitrate Vulnerable Zones and various areas at farm level (near water courses, sloping areas, wet soils, etc.). In the case of the Groundwater Directive, groundwater bodies or aquifers are distinguished. Member States have some degree of freedom to interpret the spatial variability within landscapes according to these directives.
- **Air related policies** (Air Quality Directive, NEC and IPPC Directives): the main environmental targets relate to emission ceilings at national level, concentration levels in the air and the implementation of best available techniques at farm, car, machine and company level. Its spatial component depends on envisaged measures and the target. The landscape scale is to some extent addressed in the case of the protection of sensitive areas (e.g. permit for farm extension close to a Special Area of Conservation). However, there is potential for greater consideration of landscape planning approaches as a means to maximize the environmental benefit for any given national emissions ceiling.
- **Nature protection policies** (Habitats Directive, Birds Directive): these policies have a strong spatial component through the identification of high nature value areas

(Special Areas of Conservation and Special Protection Areas, making up the Natura 2000 network). It is left to the Member States to identify and to prescribe conditions and measures applicable to these areas, and also around these areas. For example, some Member States have restrictions on farming activities, especially on the intensification of farming activities within and near Natura 2000 areas (see e.g. Hertel *et al.*, 2009). Up to now, the assessments generally only consider the location of point sources, e.g. animal housing. Diffuse sources, such as fertilizer and organic manure application, are rarely considered, but have significant local impacts. There is potential for further use of buffer zones in source areas for both atmospheric and water based nitrogen inputs.

- **Rural Development Regulations and Agri-Environmental Regulations** have a strong spatial component. Farmers in less favourable areas and/or near high nature value areas may be supported in exchange for landscape maintenance and forbearance of intensification of farming activities. Farmers may also receive support for introducing low-$NH_3$ emissions techniques for manure storage and application. The landscape perspective also provides the means to link EU agri-environment support more effectively through 'cross compliance' with other Directives. For example, where farm management plans associated with support payments are considered as 'plans or projects' under the Habitats Directive, landscape analysis provides the means to optimize spatial $N_r$ management.

In summary, there are a large number of opportunities provided by EU Directives and Regulations to address the landscape scale. These are needed to better account for local conditions in relation to the wide variety of farming systems and environmental conditions. As yet, there is a huge difference in the interpretation of the EU Directives and Regulations between Member States, and this also is also the case for addressing the landscape scale. This is notably the case with the Nitrates Directive (Smith *et al.*, 2007) and protection of the Natura 2000 areas (COST 729, 2009). Our analysis suggests that there are ample possibilities to address the landscape scale, with so far only limited use being made of this scale. Up to now, the policy-maker is faced with a lack of practical tools for supporting this type of analysis, such as user-friendly landscape models. Moreover, there is a need for case studies and improved databases for analysis at this scale.

### 11.6.4 The importance of detailed and simple tools for landscape assessment

All the cases described above have highlighted the relevance of the landscape scale for N assessment and management. However, no simple rule exists of how to make an assessment of an environmental measure or abatement technique at the landscape scale. Depending on the level of detail to be applied, this may need to consider a large number of N sources and sinks, with complex and changing relationships between them. Hence it is not straightforward to identify similarities between situations and thus to extrapolate a conclusion for one location directly to another location/situation or to derive simple rules that are generally applicable at the landscape scale. It is clear that comprehensive modelling will be the privileged approach to investigate potential strategies and make an assessment of measures and scenarios at the landscape scale. This requires detailed modelling of processes, as described in Section 11.4. Application of such models to multiple cases and/or regional or larger scales would need detailed landscape databases and the development of landscape typologies.

Nevertheless, it is clear that simple practical tools are also needed. While detailed approaches are needed to understand and quantify the interactions, the outcomes of such models also need to be generalized. In this respect, the development of publicly accessible screening tools provides an important step forward. These simpler models can be based on simplifying assumption allowing analytical relationships to be derived or on simpler numerical schemes. This makes it possible to investigate with reasonable accuracy the flows (including input to sensitive ecosystems) and concentration fields of N species. For example instead of using complicated atmospheric transport models Rihm and Kurz (2001) used a function of deposition vs. distance that was developed for the Netherlands (10-year average, averaged over all wind directions) and applied it to Switzerland. It was coupled to a spatially detailed $NH_3$ emission inventories ($200 \times 200$ m$^2$ or less), that formed the input for the calculations of $NH_3$ concentration fields. Although this should not be done in principle as the Swiss climate differs from the Dutch climate, a good correlation was obtained between modelled and measured values for 17 sites. Later Thöni *et al.* (2004) refined the method adjusting the function deposition vs. distance, so that an optimum correlation was obtained for the Swiss situation. Similar examples can be found in other countries (e.g. the SCAIL model in the UK; Theobald *et al.*, 2009) and for hydrological modelling (e.g. Durand and Torres, 1996) or ecosystem models (e.g. Strayer *et al.*, 2003).

## 11.7 Future challenges

The examples above have shown that analysing the N cascade at the landscape scale make it possible to integrate the major processes that modify the N flows and balance. To this extent, the landscape scale also appears to be a very practical scale for implementing and assessing environmental measures. However, it is also highlighted that analysing and modelling landscape interaction for N is a complex task and that no approach has yet been found to be completely satisfactory for the complete analysis. At the same time, there is a parallel need for the development of simple practical tools that can support landscape level decision making in the rural environment.

The major questions faced for the coming years include the following.

**How do we best account for the interactions between farming systems and landscape?** Spatial heterogeneity, as well as interactions with farm management, is shown to have strong effects on N flows and transformation at landscape scale. As exemplified in Figure 11.1 farm activity may determine the spatial arrangement of fields, roads and hedgerows. Moreover farm activity and hence N application to land is not only organized according to the distance from the farm (Figure 11.5) but also to the topography (e.g. grasslands are often located in wetter and less productive areas). These interactions are complex and dependent on local conditions. Hence, there is a need for more study and analysis on the interrelationship between farming systems and landscape features.

**How can we develop a landscape typology to describe landscape variety in modelling at European scale?** European rural landscapes present a wide range of variability, due to climate, physical environment (e.g. topography, soils) and history. Moreover, experiences in landscape modelling have shown that it requires detailed local data, including spatial data on activities/environmental variables, etc. National average data are usually not sufficient to represent local spatial and temporal (diurnal, seasonal or inter-annual) variability. Consequently, there is a need to develop methods to derive a landscape typology giving a limited number of landscape classes based on landscape features and farming systems. These could be based on either real landscape description using aerial photography or remote sensing, or on a farming system approach (see e.g. Figure 11.7) or both. Such a landscape typology would allow landscape processes to be treated more effectively in larger-scale operation models.

**Is it feasible to derive scenarios of future landscapes at 2030 or 2100 horizon?** Due to different drivers such as climate change, population increase, extension of urban areas or changes in agricultural and environmental policies, European rural landscapes are expected to change significantly in the next few decades. This could have a significant effect on N flows and efficiency of policy measures. There is a need to examine potential scenarios for future landscape structure and dynamics in order to account for this in climate change and land use change scenarios.

**How do we develop and test monitoring approaches to assess N flows and budgets at the landscape scale?** While modelling at the landscape scale is now becoming firmly established, as illustrated by the studies described above, monitoring approaches for landscape level assessment also need to be developed further, at least to enable the validity of the landscape modelling to be tested. This monitoring should integrate measurement of the spatial and temporal variability of $NH_3$, $N_2O$, $NO_x$ and $NO_3^-$ including the role of hot-spots. Further testing and verification of bioindicators of N responses could be integrated with the physicochemical monitoring activities.

**How do we best account for landscape issues in environmental N policies?** Landscape scale models should be adapted for practical use by landscape planners, farm advisers or policy-makers. This effort will also need databases based on case studies which could be used as a basis for analysis. The use of a landscape typology (see above) would make it possible to integrate and make assessments at a larger scale. There is an ongoing need for simple tools to support the implementation of landscape scale N policies, complementing the detailed models.

**How do we assess pollution swapping?** In the frame of environmental policies, the risk of pollution swapping (within or beyond the landscape) is increasingly important and must be further explored. The landscape scale is especially relevant, as N transformations often occur in locations different from where N has been applied. Landscape scale modelling can help to understand the origin and magnitude of these transformations by linking together the processes between landscape elements, allowing the synergies and trade-offs to be better quantified.

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